The Development of Erosion and Impact Resistant Turbine Airfoil Thermal Barrier Coatings

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This work was supported by NASA Fundamental Aeronautics Program
ECI-Thermal and Environmental Barrier Coatings
Irsee, Germany, August 15, 2007

Thermal barrier coatings are used in gas turbine engines to protect engine hot-section components in the harsh combustion environments and extend component lifetimes. For thermal barrier coatings designed for turbine airfoil applications, further improved erosion and impact resistance are crucial for engine performance and durability. Advanced erosion resistant thermal barrier coatings are being developed, with a current emphasis on the toughness improvements using a combined rare earth- and transition metal-oxide doping approach. The performance of the doped thermal barrier coatings has been evaluated in burner rig and laser heat-flux rig simulated engine erosion and thermal gradient environments. The results have shown that the coating composition optimizations can effectively improve the erosion and impact resistance of the coating systems, while maintaining low thermal conductivity and cyclic durability. The erosion and impact damage mechanisms of the thermal barrier coatings will also be discussed.

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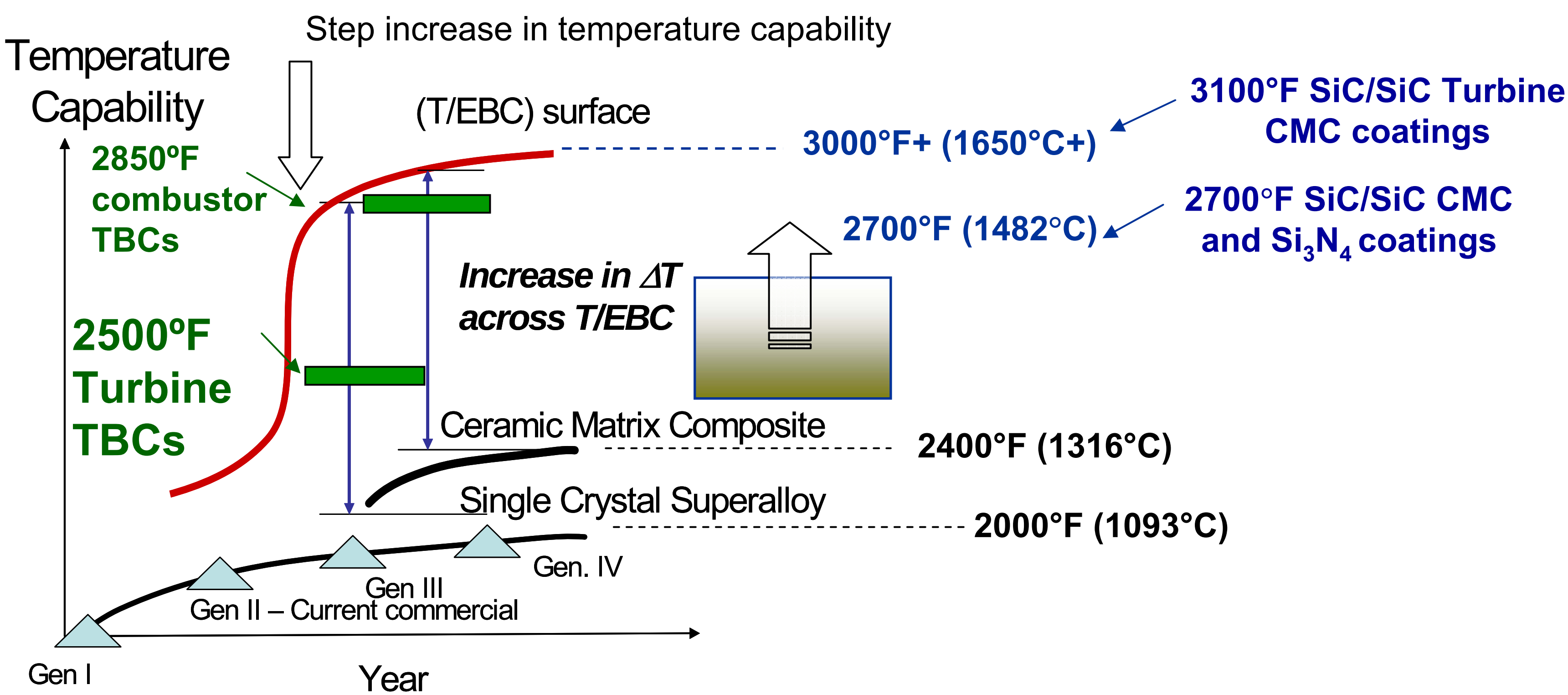
SUNY Stony Brook
Mesoscribe Technologies
Penn State University

Motivation

— **Thermal barrier coating (TBC) system development goals**

- Emphasize high heat-flux cyclic durability
- Improve turbine airfoil thermal barrier coatings up to 3x erosion resistance



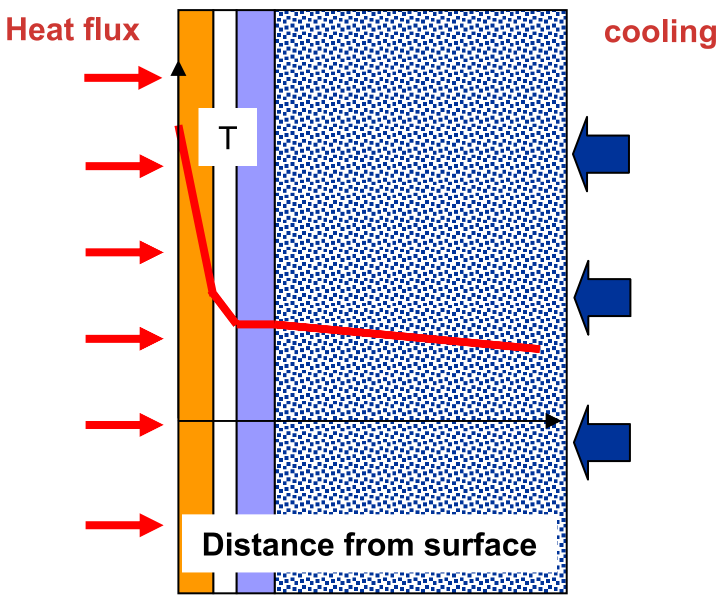
Outline

- High-heat-flux erosion test capability
- Low conductivity thermal barrier coating updates
- Advanced erosion resistant low conductivity coating development
- Erosion and impact damage observations
- Summary

High-Heat-Flux Tests Critical to Turbine TBC Development

– High-heat-flux laser test approach for thermal barrier coating cyclic durability

- Temperature gradient requirements: up to 200 °C/100 microns
- Heat flux requirements 200-300 W/cm^2
- Cooling also an issue in laboratory tests



NASA CO_2 Laser Rig

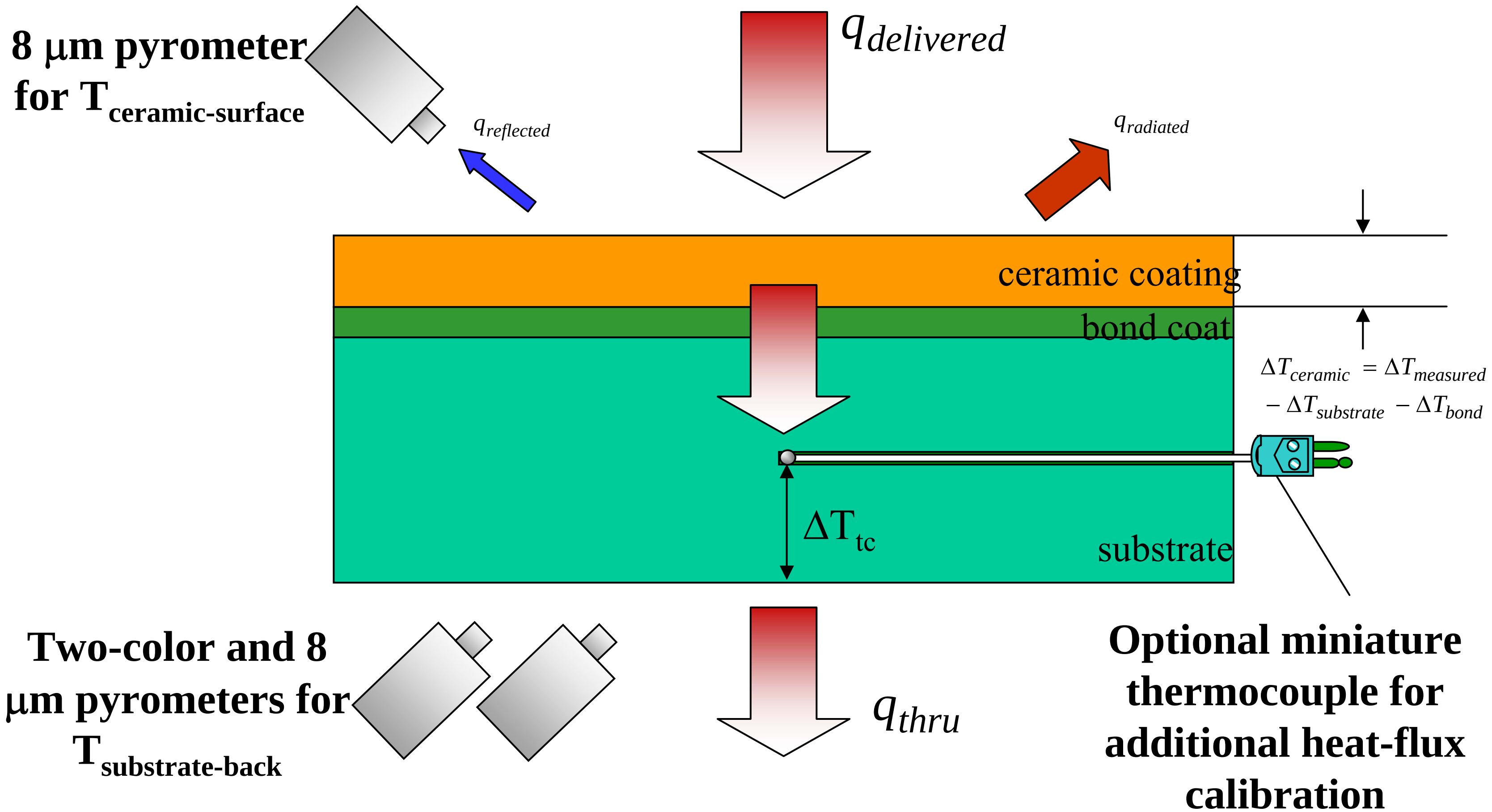
Current capability up to 315 W/cm^2

In-Situ Thermal Conductivity Measurements by a Steady-State Laser High-Heat-Flux Approach

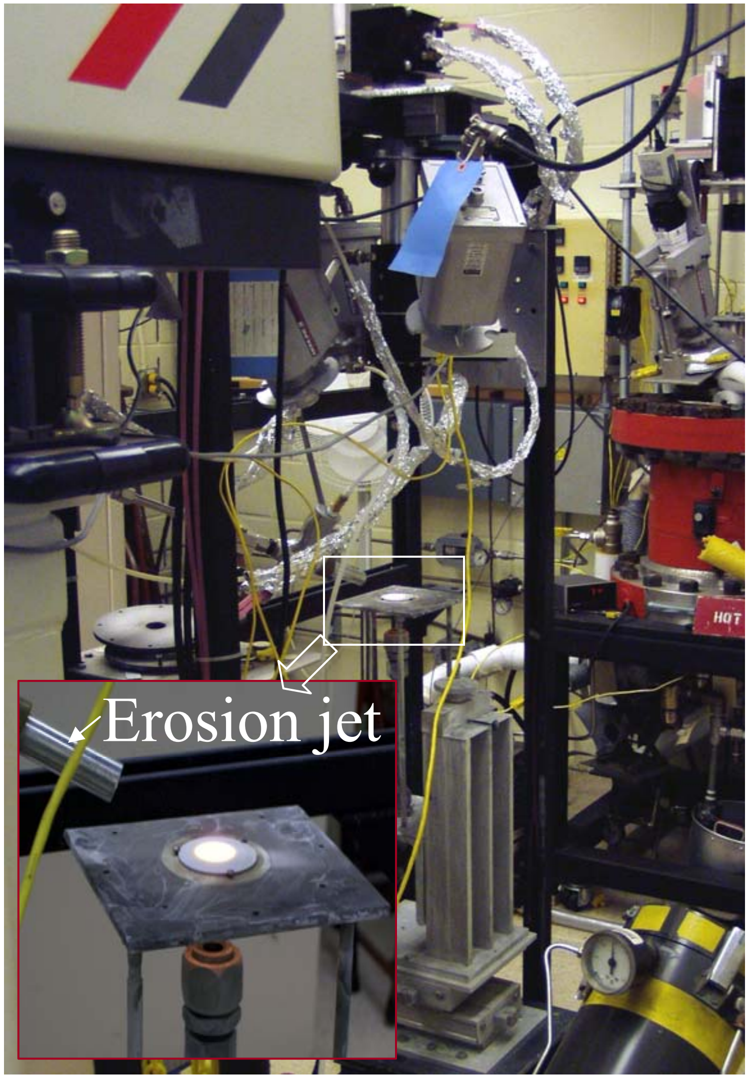
$$k_{ceramic}(t) = q_{thru} \cdot l_{ceramic} / \Delta T_{ceramic}(t)$$

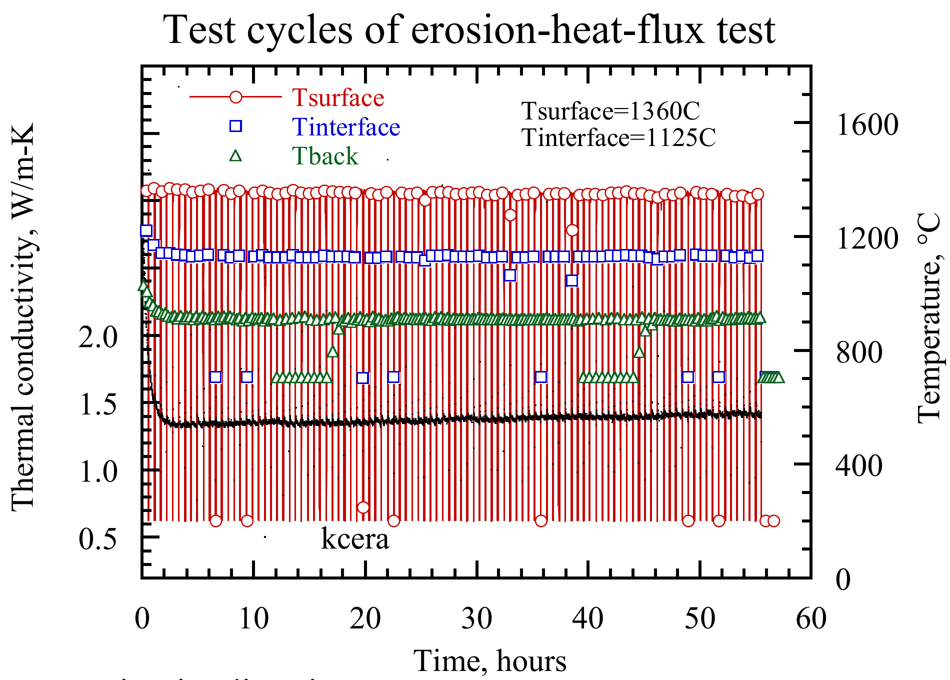
Where

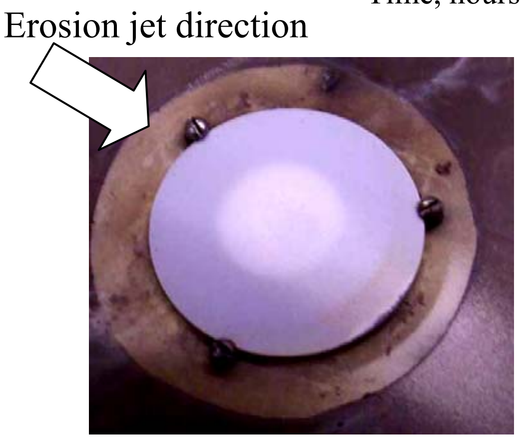
$$q_{thru} = q_{delivered} - q_{reflected} - q_{radiated} \quad \text{and} \quad \Delta T_{ceramic}(t) = T_{ceramic-surfce} - T_{metal-back} - \int_0^{l_{bond}} \frac{q_{thru} \cdot dl}{k_{bond}(T)} - \int_0^{l_{substrate}} \frac{q_{thru} \cdot dl}{k_{substrate}(T)}$$



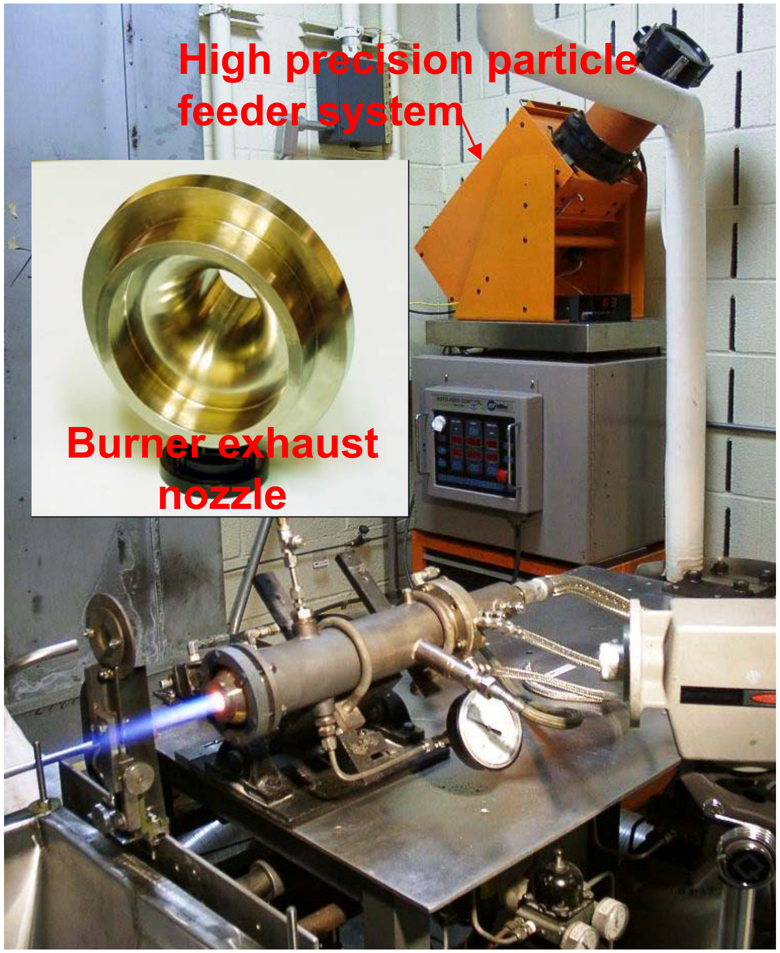
Laser High-Heat-Flux Erosion Test Rig

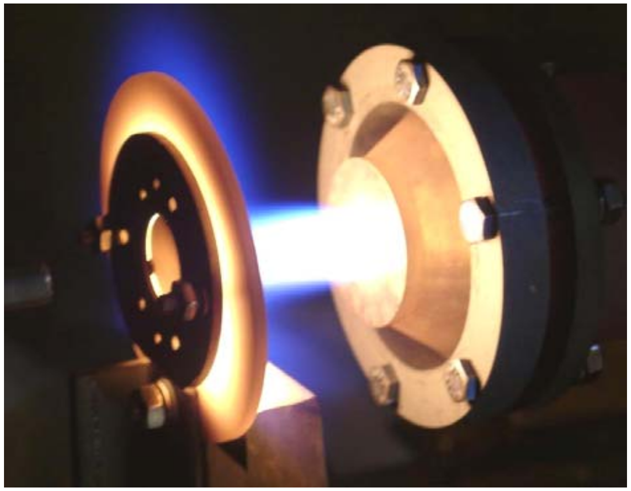






Mach 0.3-1.0 High Velocity Burner Erosion Test Rig





Low Conductivity Thermal Barrier Coating Design Requirements

- **Low conductivity ("1/2" of the baseline) retained under thermal gradient at 2400°F**
- **Improved sintering resistance and phase stability (up to 3000°F)**
- **Excellent durability and mechanical properties**
  - Cyclic life
  - Toughness
  - Erosion/impact resistance
  - CMAS and corrosion resistance
  - Compatibility with the substrate/TGO
- **Processing capability using existing infrastructure and alternative systems**
- **Other design considerations**
  - Favorable optical properties
  - Potentially suitable for various metal and ceramic components

Low Conductivity Thermal Barrier Coating Design Approaches

- **Emphasize ZrO_2- or HfO_2-based alloy systems – defect cluster approach, for toughness considerations**

- **Advantages of defect cluster approach**

  - **Advanced design approach:** design of the defect clustering

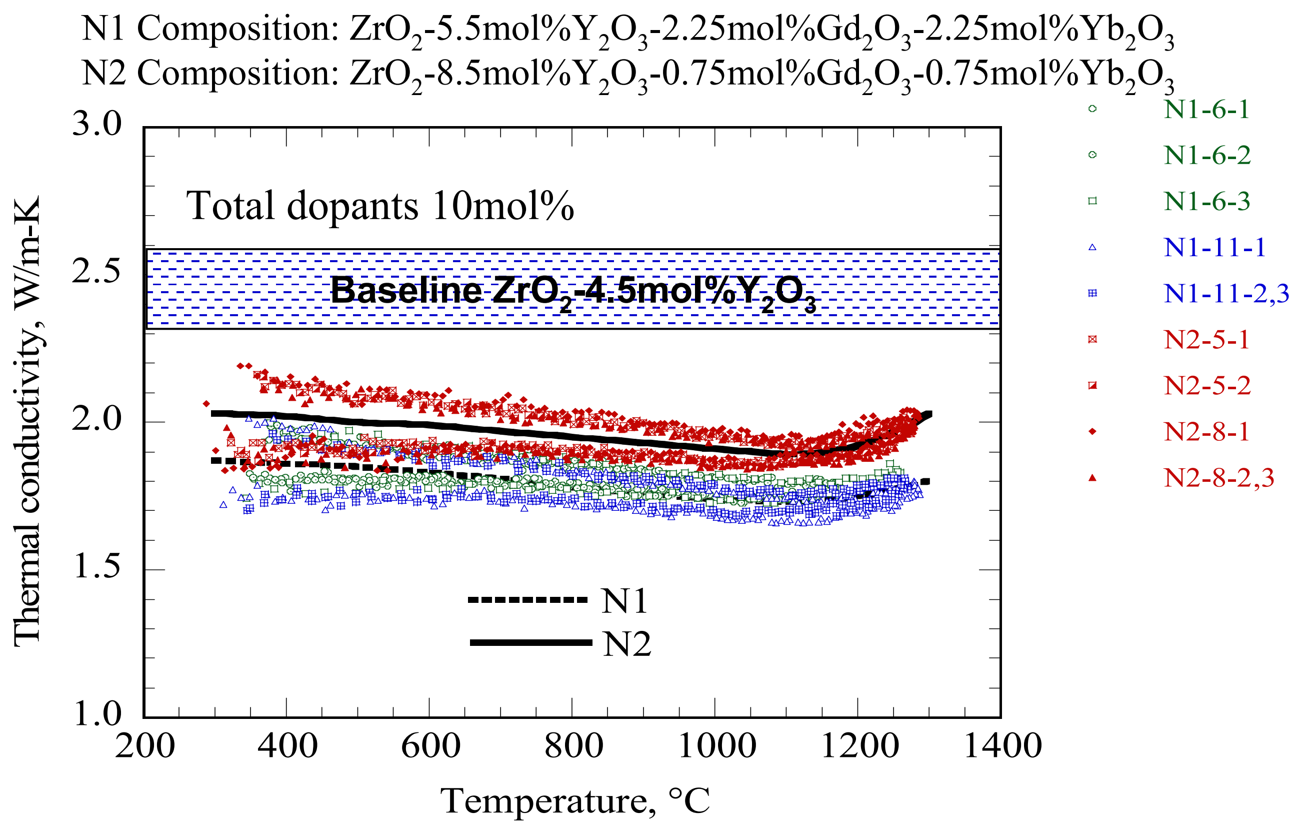
  - **Better thermal stability:** point defects and clustering are thermodynamically stable

  - **Improved sintering resistance:** effective defect concentration reduced and activation energies increased by clustering

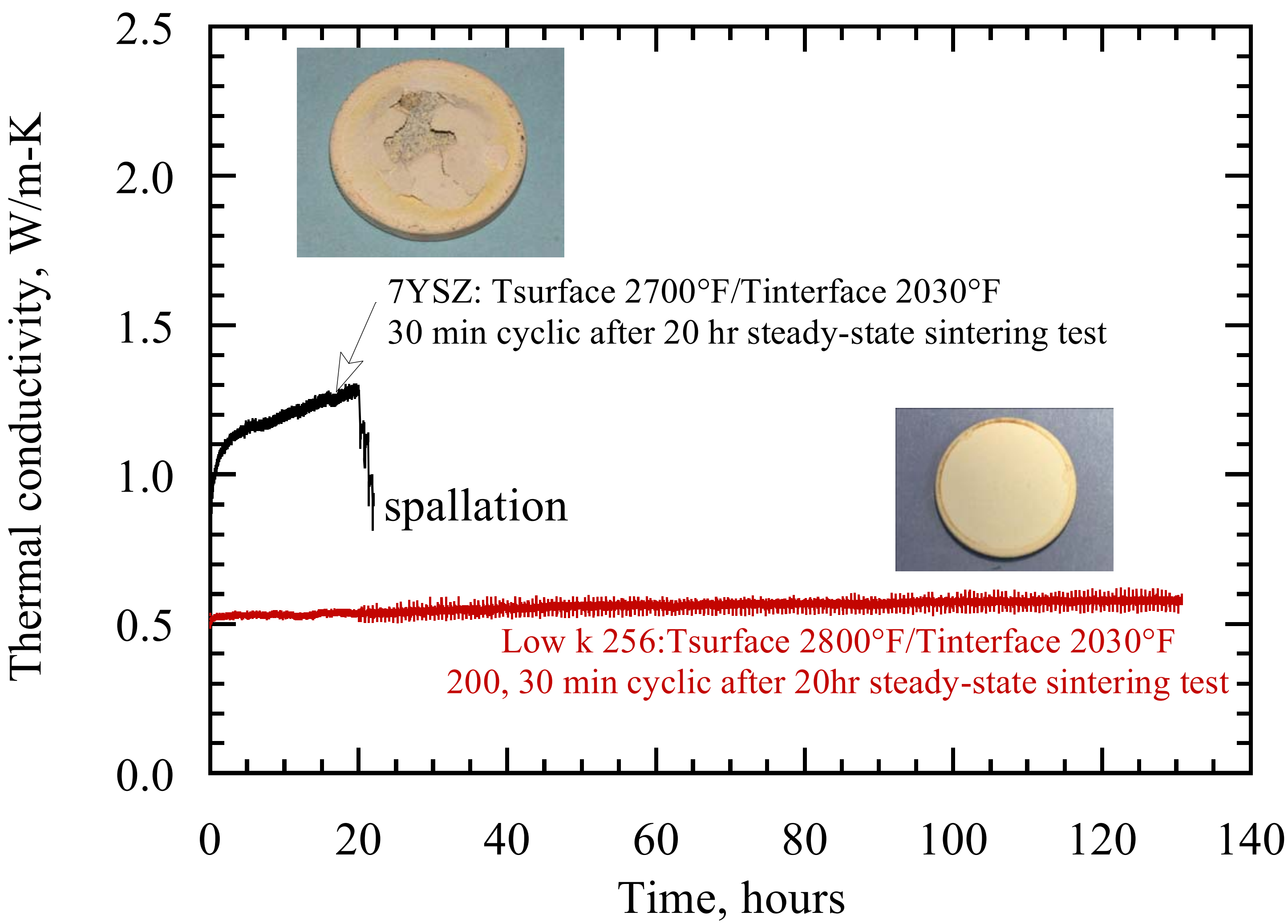
  - **Easy to fabricate:** plasma-sprayed or EB-PVD processes

Thermal Conductivity of Dense Monolithic Low Conductivity Oxides

- **Hot-pressed, fully dense (density ~6.0 g/cm^3) low conductivity oxide specimens prepared by Pratt & Whiney**
- **15% lower conductivity observed for the specimens with 3mol% higher RE cluster dopants**

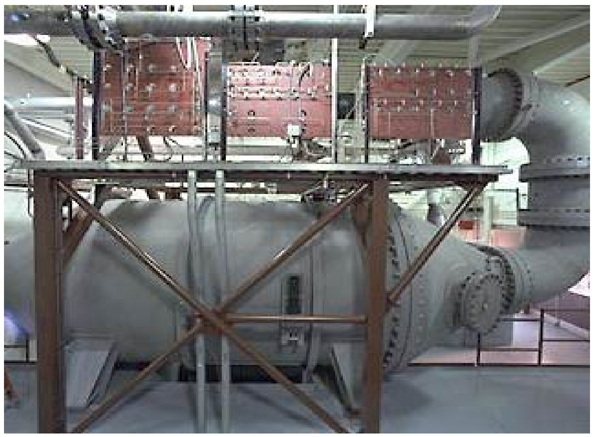


Advanced Low Conductivity Coatings for Combustor Applications

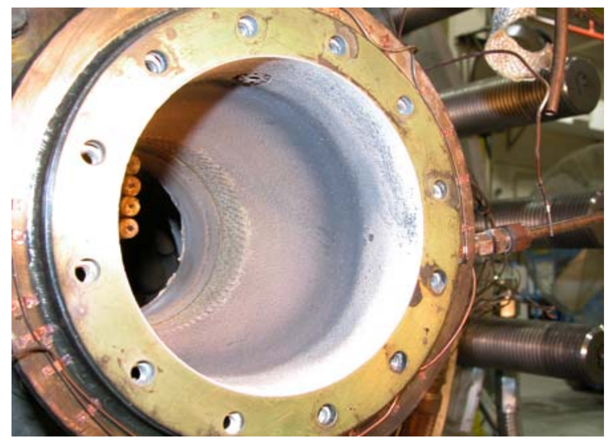


Advanced Low Conductivity Thermal Barrier Coating Demonstrations

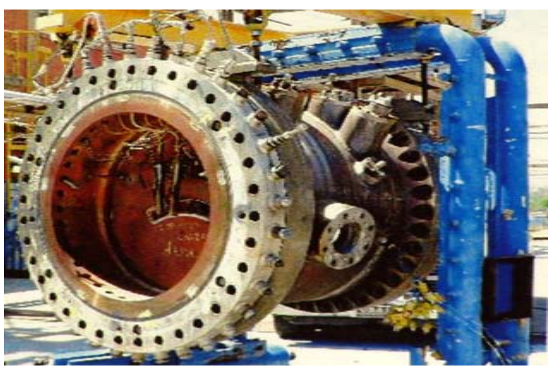
— **Coated engine components (CFM TAPS, IHPTET, JSF, Propulsion 21 engine flame tubes, combustor liners, adapters and dome plates etc) tested under simulated engine sector rig environments**



Low conductivity TBC flame tube and combustor deflector demos in Advanced Subsonic Combustion Rig (ASCR)



Low conductivity TBC Propulsion 21 flame tube and deflector demonstrations



Low conductivity TBC combustor liner demonstration in GE Trapped Vortec Combustor rig

Development of Advanced Defect Cluster Low Conductivity Thermal Barrier Coatings for Turbine Airfoil Applications

- **Multi-component oxide defect clustering approach** (Zhu and Miller, *US Patents No. 6,812,176, No.7,001,859, and 7,186,466; US Patent Application 11/510,574*)

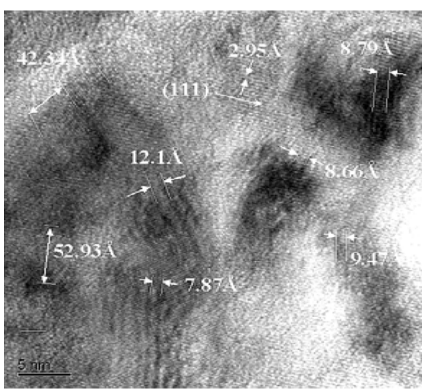
ZrO_2-Y_2O_3- $Nd_2O_3(Gd_2O_3,Sm_2O_3)$-$Yb_2O_3(Sc_2O_3)$ – TT(TiO_2+Ta_2O_5) systems

Primary stabilizer

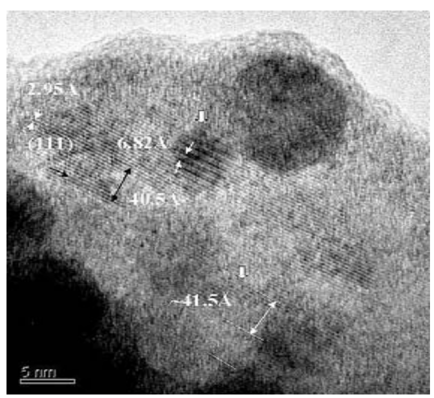
Toughening dopants

Oxide cluster dopants with distinctive ionic sizes

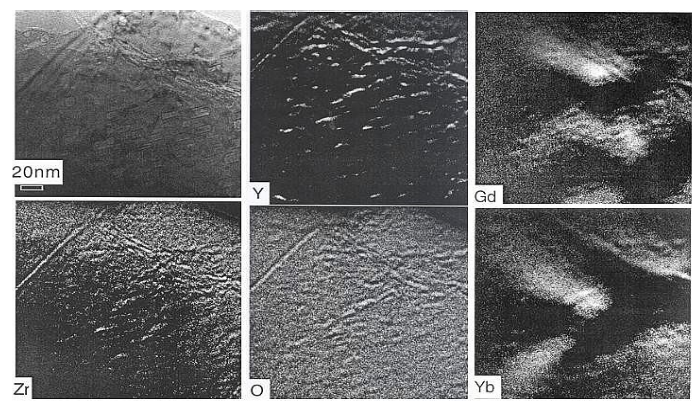
- **Defect clustering associated with dopant segregation**



Plasma-sprayed ZrO_2-13.5mol%$(Y, Nd,Yb)_2O_3$



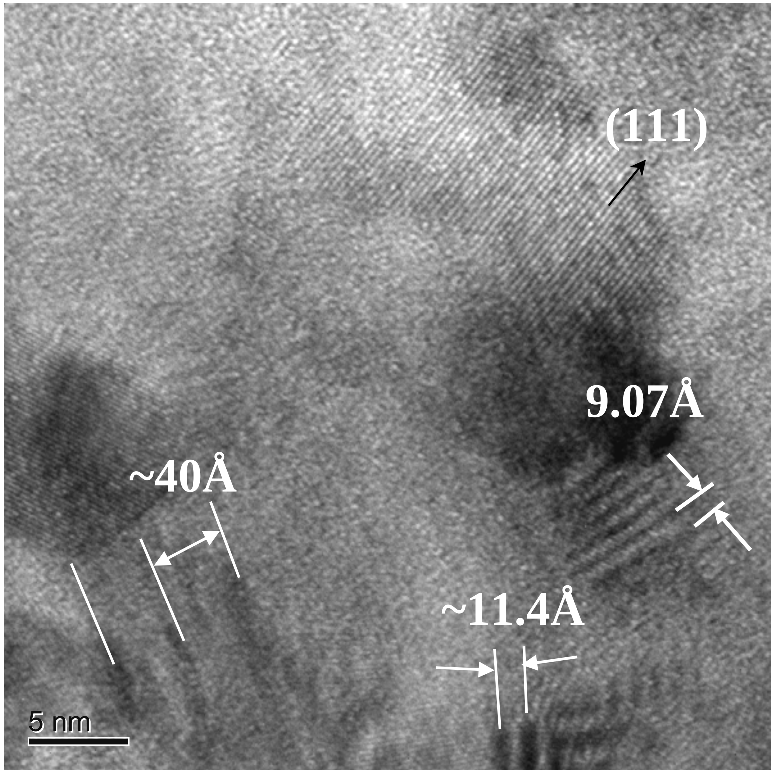
EB-PVD ZrO_2-12mol%$(Y, Nd,Yb)_2O_3$



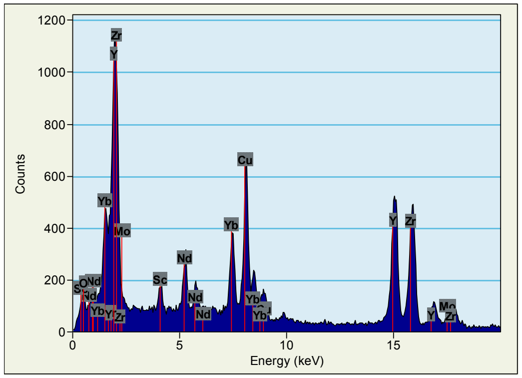
EELS elemental maps of EB-PVD ZrO_2-14mol%$(Y, Gd,Yb)_2O_3$

Defect Clusters in a Plasma-Sprayed Y_2O_3, Nd_2O_3 and Yb_2O_3 Co-Doped ZrO_2-Thermal Barrier Coating

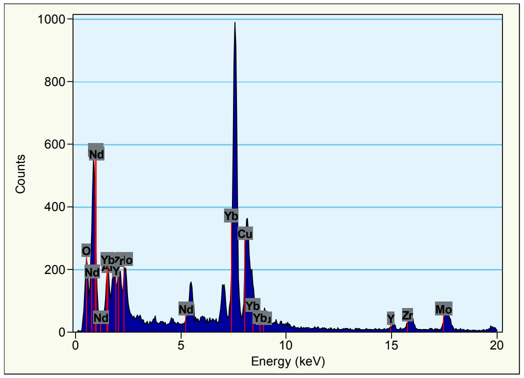
— Yb, Nd rich regions consisting of small clusters with size of 5 to 20 nm



Nd and Yb rich region clusters



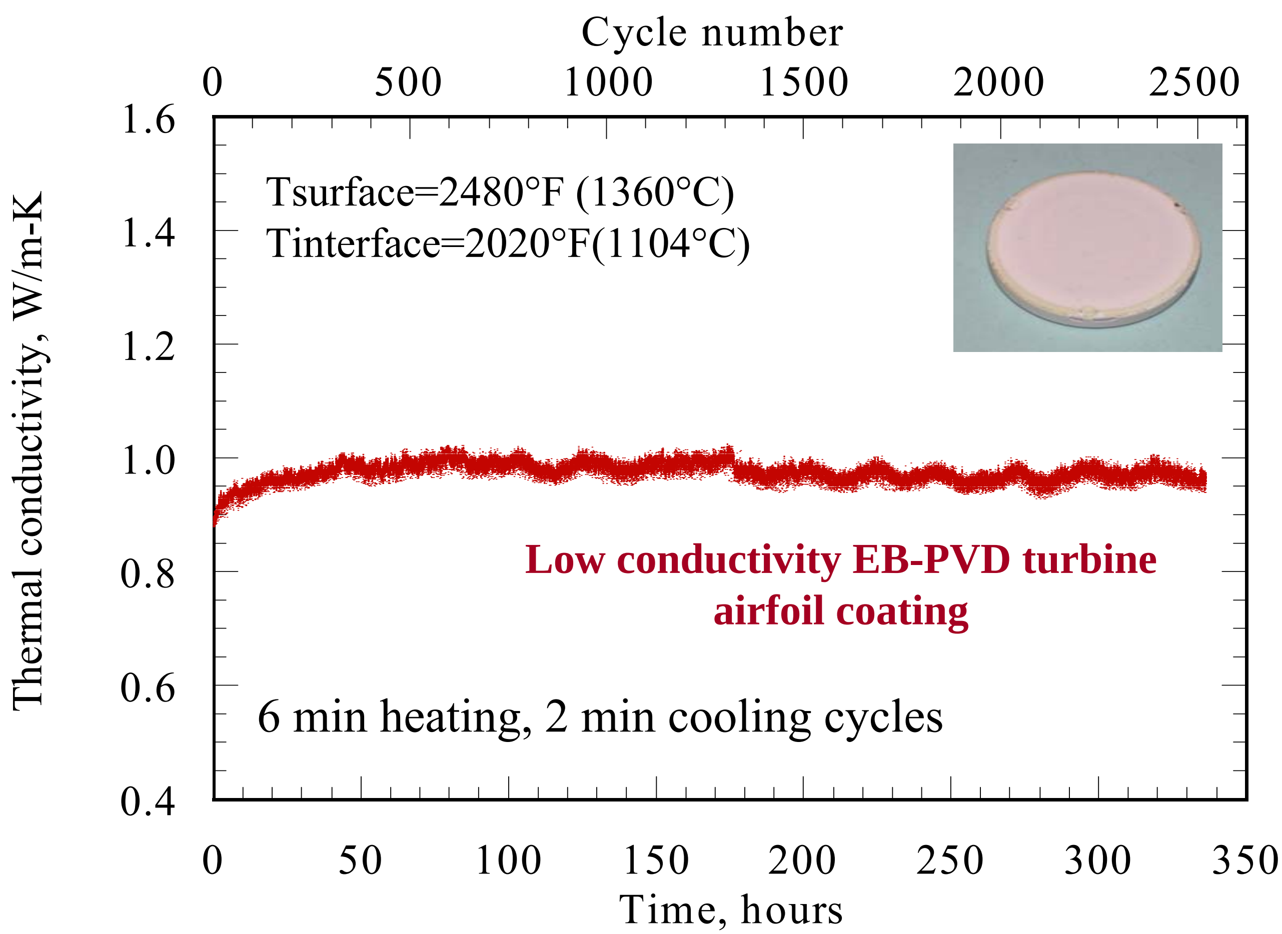
Overall EDS



Yb and Nd rich region EDS

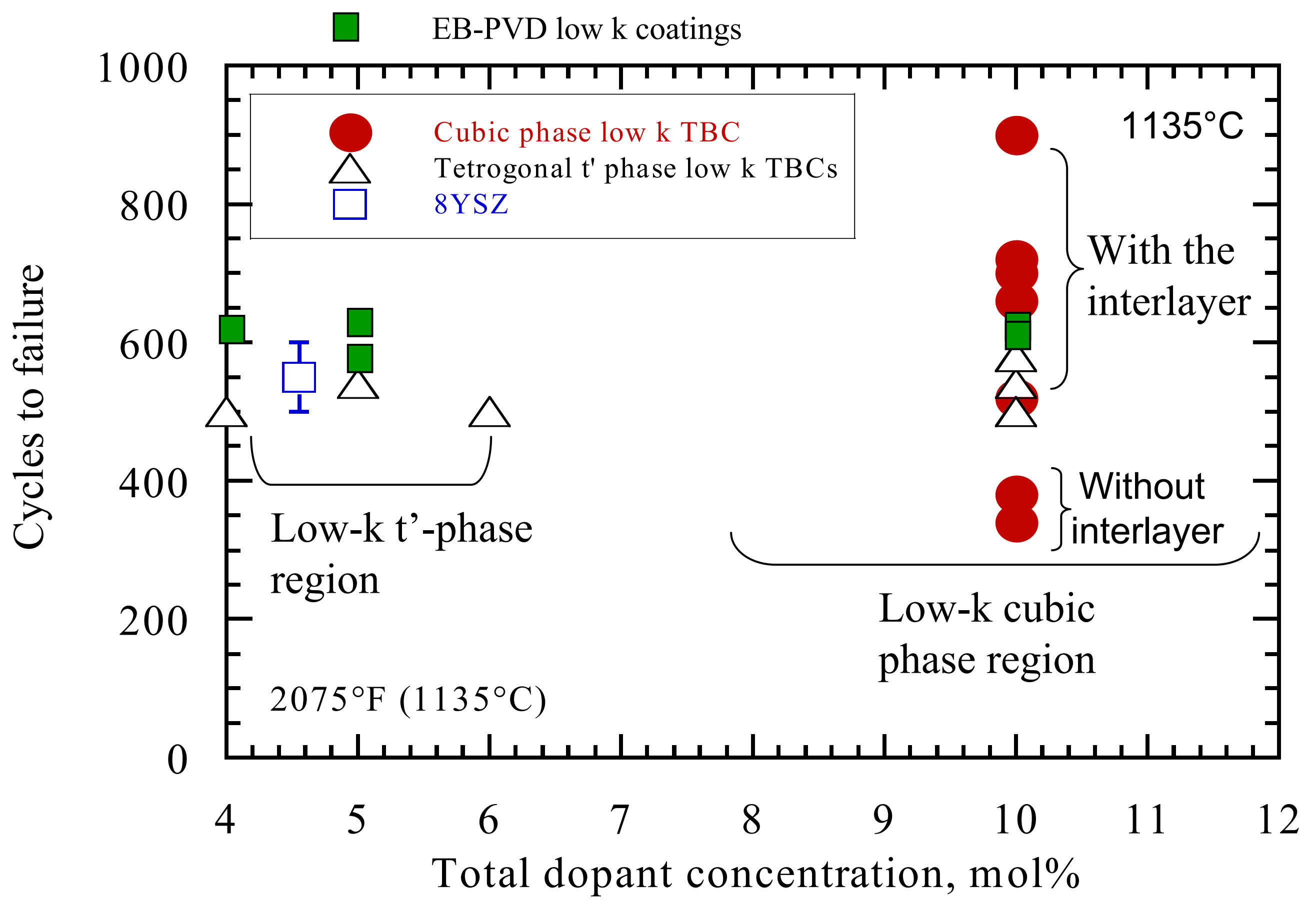
Advanced Low Conductivity Coatings Showed Excellent High Temperature Cyclic Durability

— **The low conductivity turbine airfoil thermal barrier coatings successfully tested under simulated engine thermal gradient cyclic conditions**



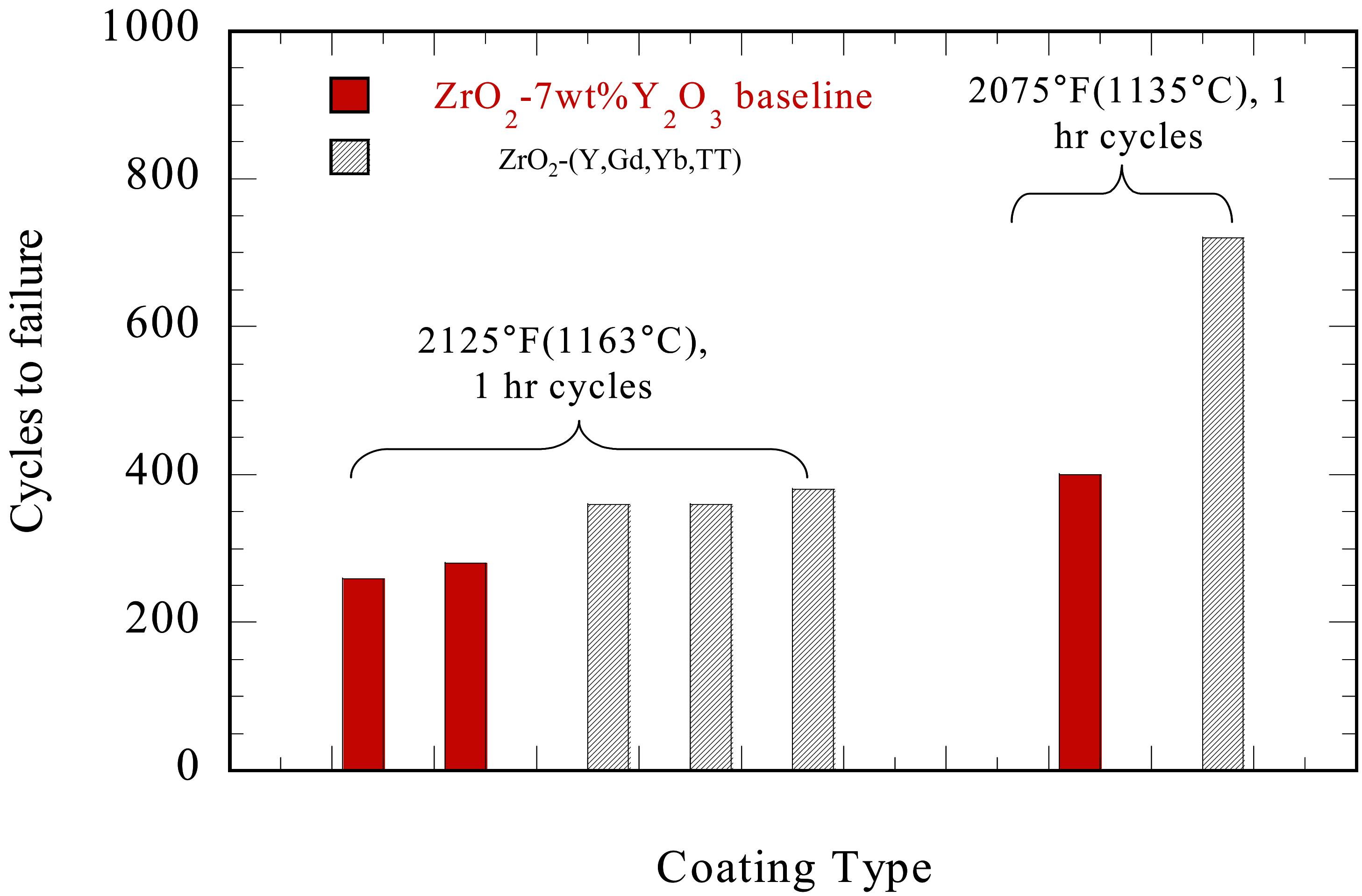
Furnace Cyclic Behavior of ZrO_2-$(Y,Gd,Yb)_2O_3$ Thermal Barrier Coatings

- The cubic-phase ZrO_2-based low conductivity TBC durability improved by a thin 8YSZ or low k t'-phase interlayer
- The t'-phase based low conductivity TBCs had excellent furnace cyclic life



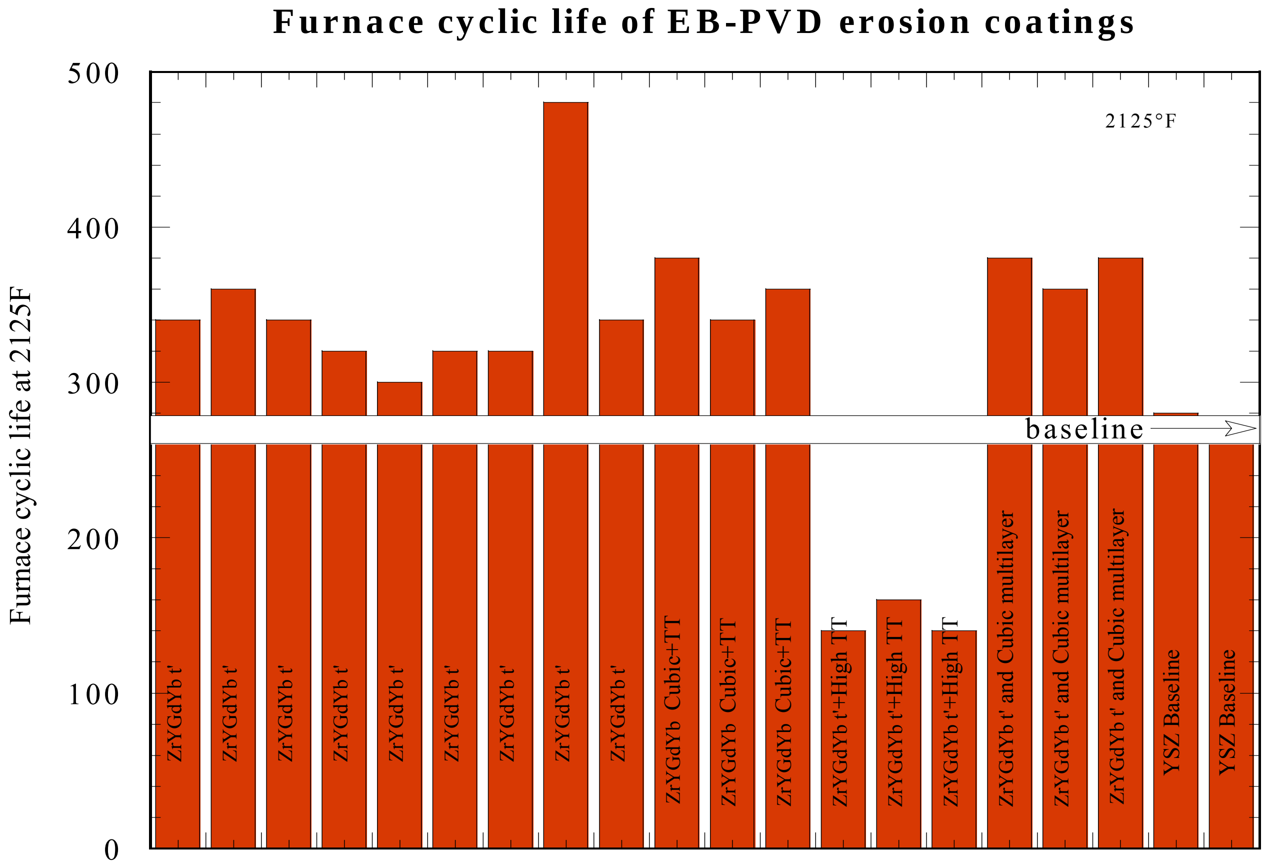
Furnace Cyclic Behavior of ZrO_2-$(Y,Gd,Yb)_2O_3$ TBCs Co-doped with TiO_2 and Ta_2O_5

— **Effect of temperature on coating cyclic life**



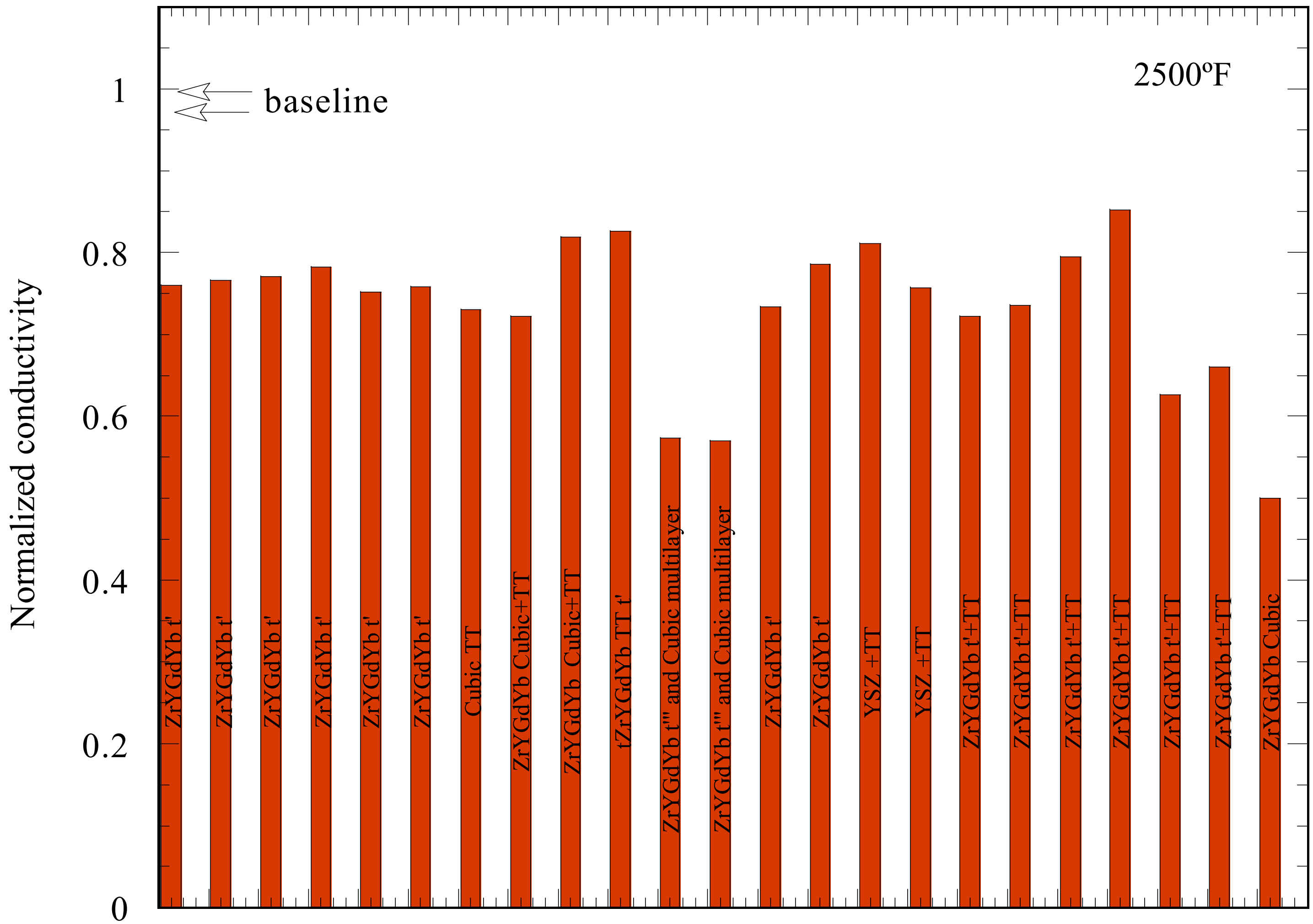
Furnace Cyclic Behavior of ZrO_2-$(Y,Gd,Yb)_2O_3$ Co-doped with TiO_2 and Ta_2O_5

- **ZrO_2-Y_2O_3-Gd_2O_3-Yb_2O_3 and ZrO_2-Y_2O_3-Gd_2O_3-Yb_2O_3-TT coatings designed for improved cyclic and erosion resistance**
- **Focusing on *t'* and *t'-nano clustering (cubic)* phase systems**



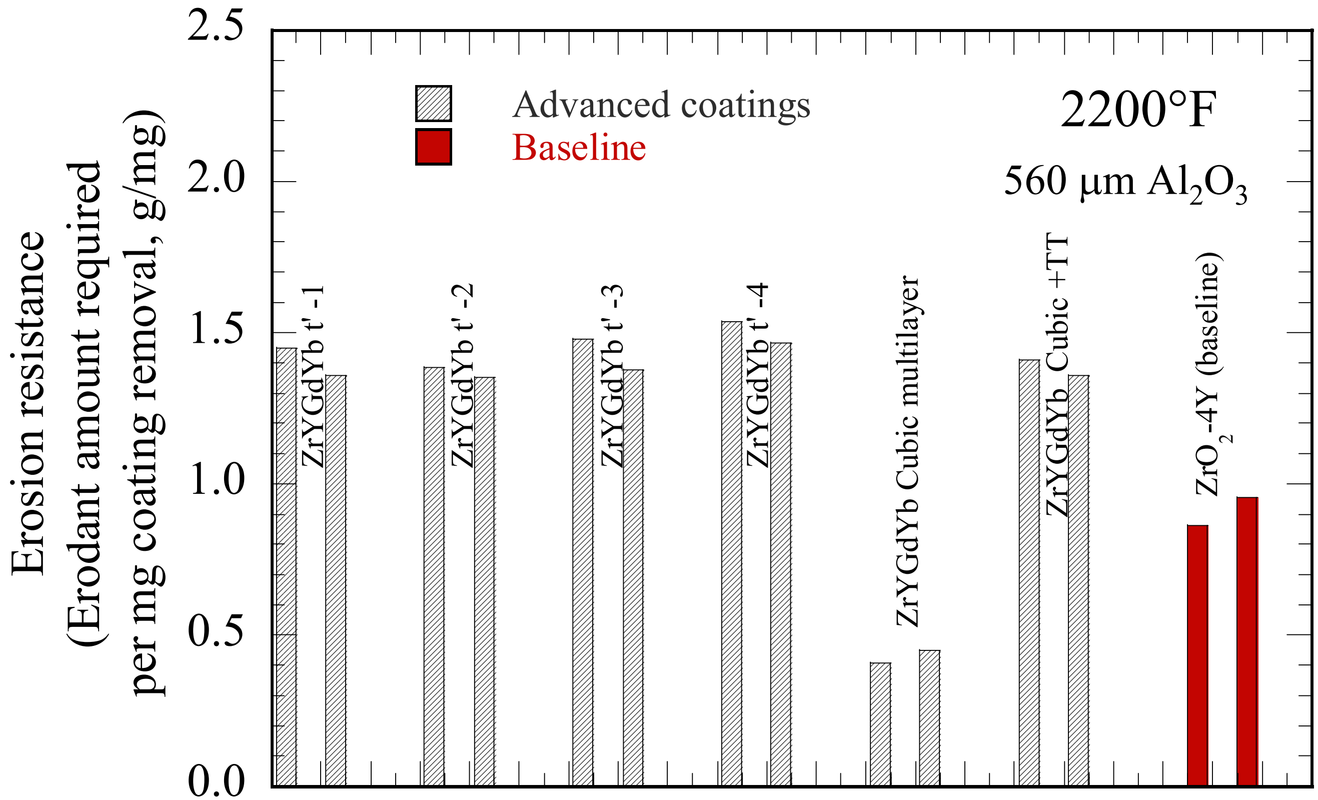
Thermal Conductivity of ZrO_2-$(Y,Gd,Yb)_2O_3$ and ZrO_2-$(Y,Gd,Yb)_2O_3$ + TT(TiO_2-Ta_2O_5) Systems

Thermal conductivity of EB-PVD erosion TBCs



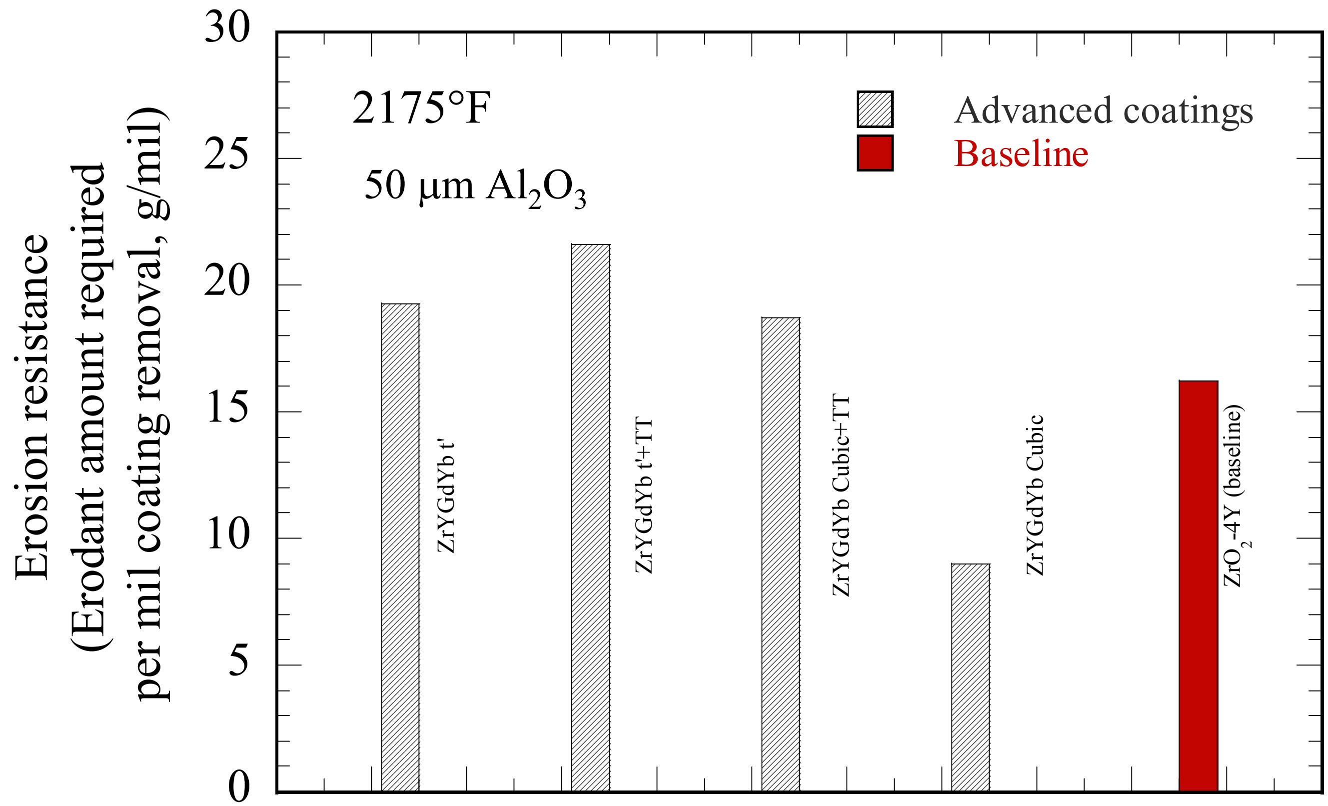
Erosion Resistance of Advanced Multi-component Low Conductivity Thermal Barrier Coatings

— **Improved impact/erosion resistance observed for advanced low conductivity six-component coatings**



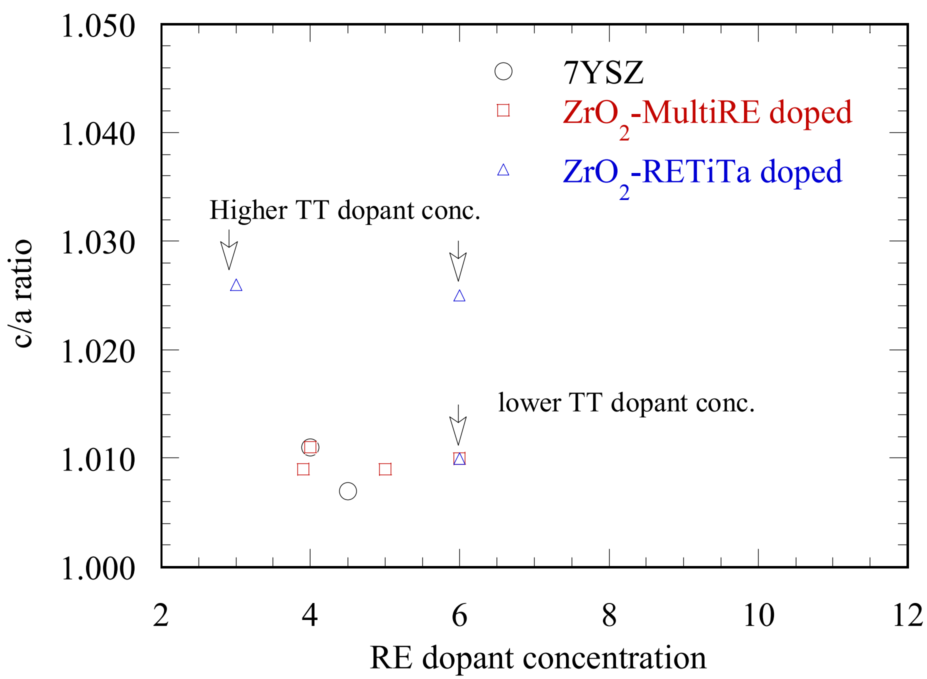
Erosion Resistance of Advanced Multi-component Low Conductivity Thermal Barrier Coatings - *continued*

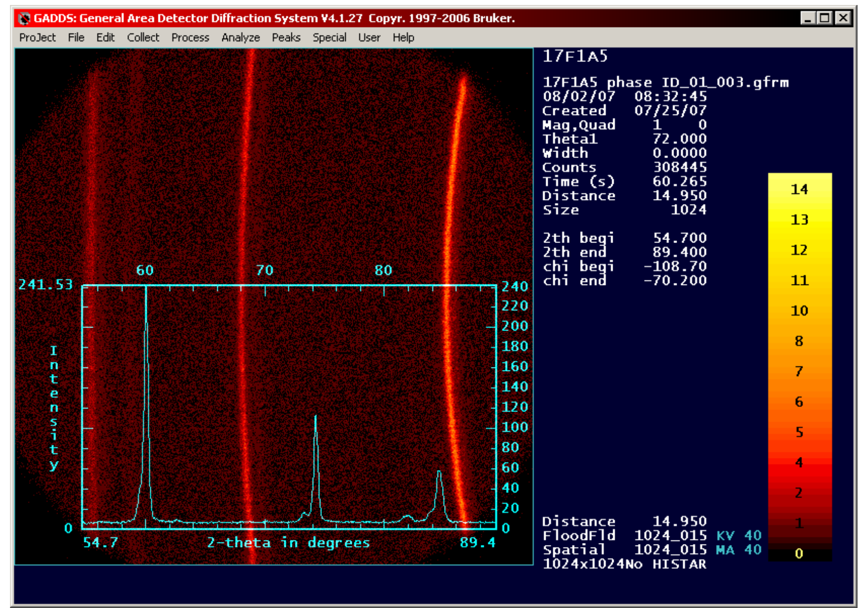
— **Improved erosion resistance demonstrated for advanced low conductivity thermal barrier coatings**



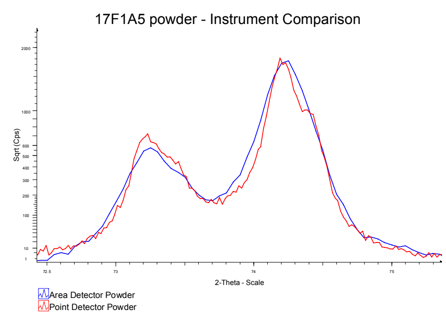
National Aeronautics and Space Administration

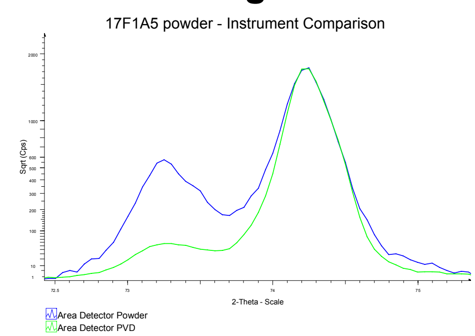
Tetragonality of Multi-Component ZrO_2 being Evaluated and Correlated to Coating Performance





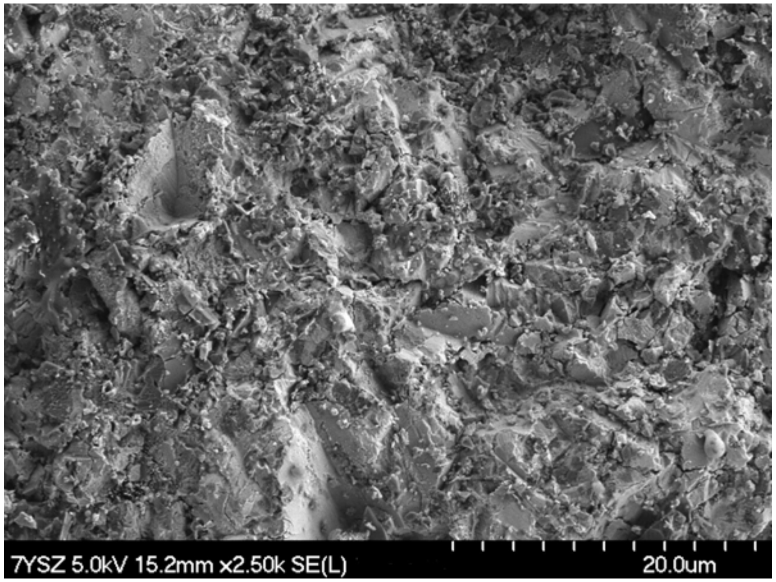
Area detector x-ray diffractometer used for EB-PVD coatings



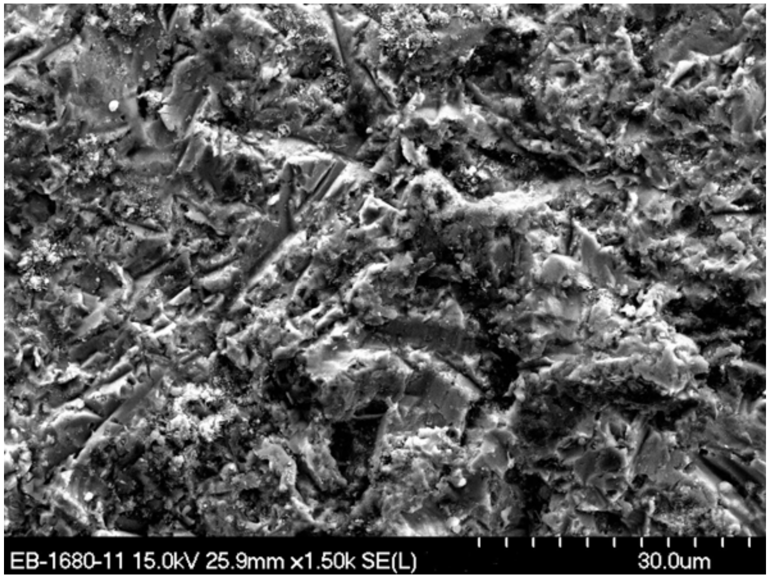


Surface Erosion Morphologies of Turbine Airfoil Thermal Barrier Coatings

— **Toughened structures observed for advanced multi-component coatings**



ZrO_2-7wt%Y_2O_3

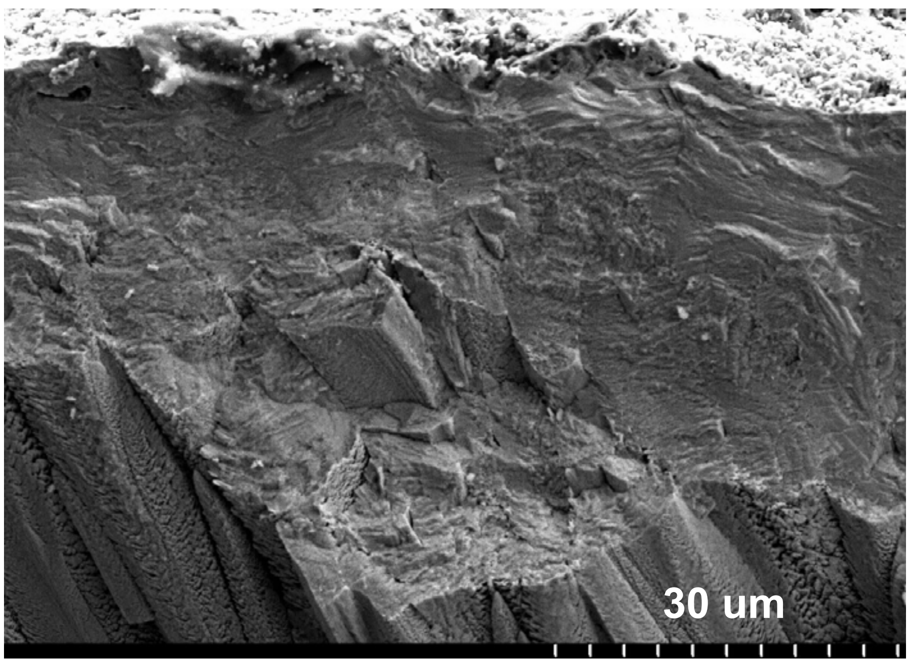


Advanced coating

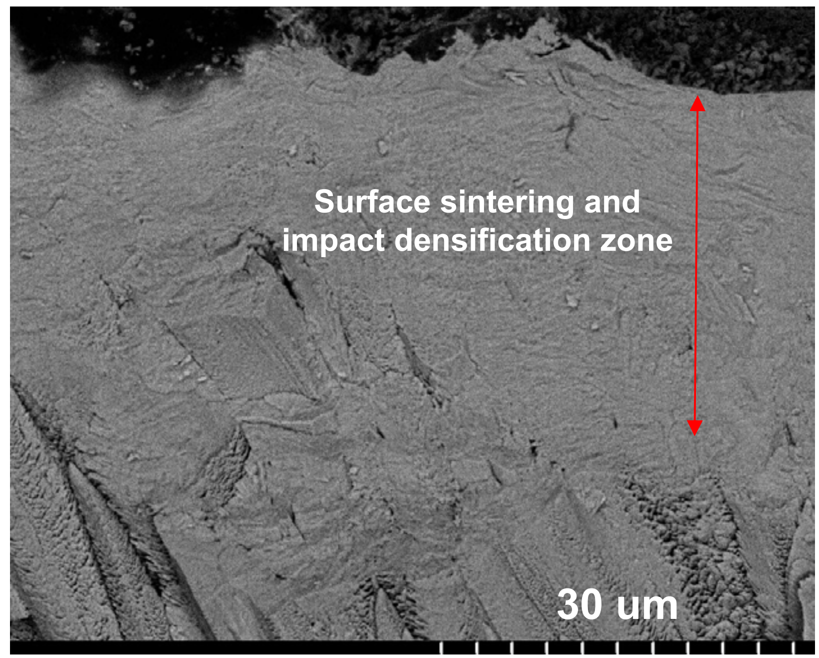
Impact Failure of Advanced Multi-Component Low Conductivity Thermal Barrier Coatings

— Surface sintering and impact densification zones observed, with subsequent spallation under the erodent further impacts
— Toughened structures observed

SEM micrographs of advanced thermal barrier coating after impact/erosion damage



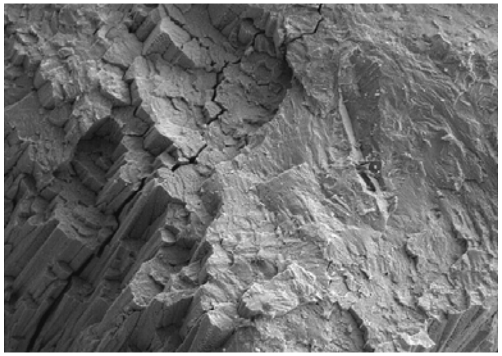
Secondary electron image

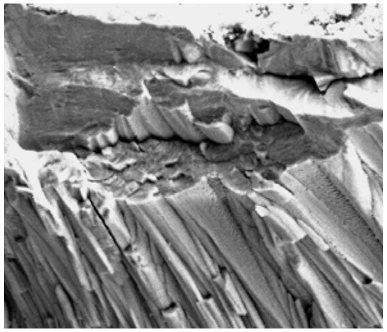


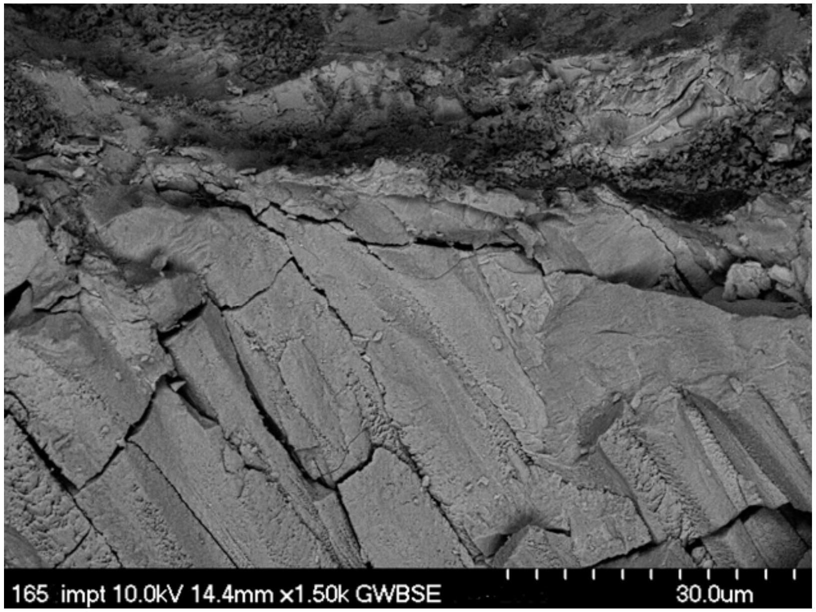
Backscattered electron image

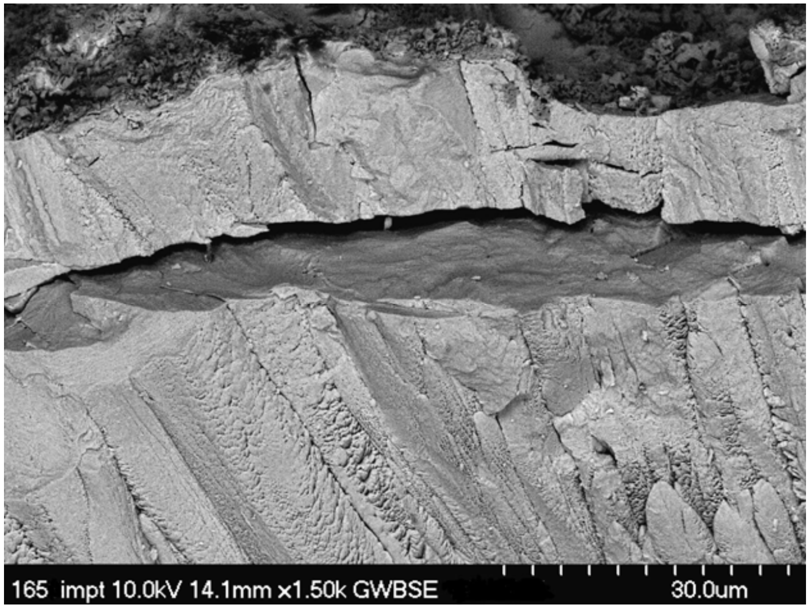
Impact Failure of Advanced Multi-Component Low Conductivity Thermal Barrier Coatings

— **Multi-level delaminations under combined impact loading and thermal gradients**



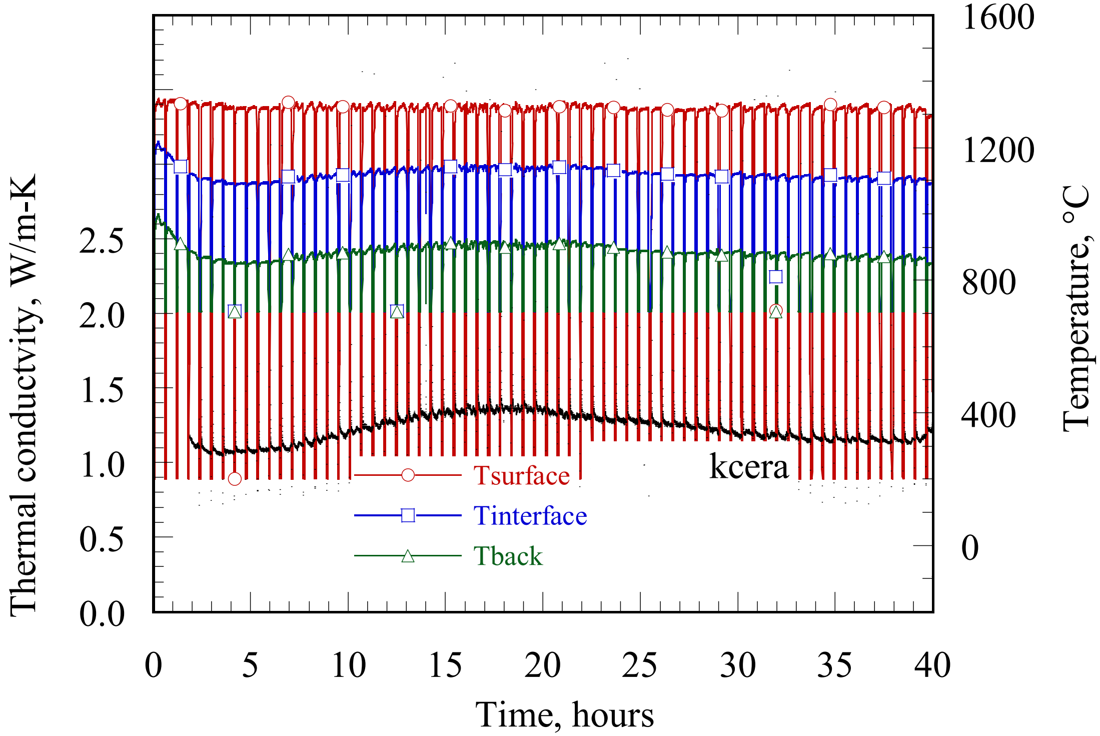






High Heat Flux Testing for Studying CMAS Effect

— Durability of advanced coatings with CMAS testing



Summary

- **High temperature erosion testing developed**
- **An interlayer coating significantly improved the furnace cyclic life of four-component "cubic" phase low conductivity TBCs**
- **Six-component with Ta, Ti coating systems improved the coating durability – advanced phase development possible**
- **Improved erosion/impact resistance observed for the multi-component coating systems**
- **Other interactions such as CMAS considered for coating composition designs**
- **Coatings being optimized for cyclic life, thermal conductivity and erosion/impact and CMAS resistance**